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Thermo-poroelastic effects on reservoir seismicity and permeability change

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ABSTRACT

In this paper we study the role of thermo-poromechanical processes on reservoir seismicity and permeability enhancement using theoretical/numerical analysis. The numerical model is fully coupled, considering non-isothermal compressible single-phase fluid flow in fractured porous rock. It combines the thermo-poroelastic displacement discontinuity method, a nonlinear joint deformation model, and a finite difference method for solving the fluid and heat transport in a fracture network. The model is applied to simulate cool water injection into fracture/matrix systems to examine the role of coupled processes on fracture deformation, matrix pore pressure and stress redistributions to assess their role in induced seismicity and permeability variations. The simulation results are analyzed to draw conclusions regarding injection rate dependence of seismicity, and its transience due to coupled processes. Thermal influence on pore pressure and stress tend to promote delayed seismicity. In presence of coupled processes, rock matrix stress perturbations due to natural fracture deformation can be an influencing mechanism for seismicity. Our results show the induced normal stress in the vicinity of the fracture center where injected water enters, can be significant for higher cooling levels in low permeability matrix, and induces additional pore pressure perturbations in the matrix. These couplings have implications for reservoir stimulation and induced seismicity in geothermal reservoirs. The reservoirrock can experience a series of induced stress/pore pressure regimes with continued cooling (under injection). A potentially destabilizing regime is followed by a stabilizing one, and subsequently the rock approaches a destabilizing state. Each situation can result in potentially different levels of MEQ activity. Finally, the impact of thermo-poroelastic stresses on injection/extraction pressure profiles in a fractured rock is illustrated. Injection pressure tends to initially increase in response to poroelastic stress, but with time the thermal effect dominates resulting in fracture aperture increases and lowering of injection pressure.

1. Introduction

Design and management of enhanced geothermal system (EGS) and hydrothermal reservoirs can benefit from simulation of coupled fracture deformation and fluid flow — since interactions among fluid and heat flow, and the mechanical response of the fracture and matrix impact reservoir permeability variations and occurrence of seismicity. The coupling between these processes during injection/extraction can be taken into account using linear theory of thermo-poroelasticity. Often, heat transport in a reservoir is dominated by advection. However, when the rock matrix permeability is low (Delaney, 1982) and fluid flows mainly within deformable fractures or a fault, conductive transport in the rock matrix leads to important phenomena related to coupling between temperature, pore pressure, and stress that may result in delayed rock matrix and/or natural fracture failure, potentially producing delayed seismicity. Although the thermo-poroelastic constitutive equations are linear, analytical solutions can be found only for relatively simple geometries and processes (e.g., Tao and Ghassemi, 2010; Ghassemi et al., 2008; Li et al., 1998; Kurashige, 1989) and the solution of problems such as injection/extraction into a deformable fracture network requires numerical modeling even in two dimensions.

Thermal and poroelastic stresses and their applications to geomechanics have been the subject of many studies. Nowacki (1973) provided a detailed exposition of theoretical and applied thermoelasticity with the solution of many problems including stresses due to heat sources with many references going back to the early 1900s. Thermoelasticity has been used to study

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thermal cracking in certain igneous rocks (Fredrich and Wong, 1986). In the petroleum sector, the role of thermal stress on seismicity (Ghassemi et al., 2007; Bruel, 2002; Stark, 1990) and injection operations has been studied (e.g., Perkins and Gonzalez, 1985). There have also been a number of early investigations of thermoelastic effects in geothermal systems and earth science (Bodvarsson and Lowell, 1972; Knapp and Norton, 1981). A coupled hydro-thermo-mechanical model was developed by Kohl et al., 1995 using the finite element method. The model was used to study the impact of thermal and poroelastic stresses on flow impedance. Other poro- and thermoelastic models consider multiple fractures in 3D (Safari and Ghassemi, 2015) for MEQ analysis. The focus of this paper is a more detailed analysis of thermo-poromechanical coupling effects. In this work, a two dimensional displacement discontinuity model is used to examine various coupling mechanisms and their roles on fracture deformation, and the stress state variations within the rock matrix. This is in extending our previous work where the focus was mostly on injection pressure. The model addresses the impact of fracture deformation and transport processes on the re-distribution of stress and pore pressure fields in a geothermal reservoir. The latter provides valuable insight on the role of coupled processes on induced seismicity and its dependence on injection rates and temperatures.

2. Thermo-poroelasticity

The constitutive equations of the linear theory of thermo-poroelasticity are given by McTigue (1986a,b) as:

$$\varepsilon_{ij} = \frac{1}{2G}\left[\sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij}\right] + \frac{\alpha(1-2\nu)}{2G(1+\nu)}\delta_{ij}p + \frac{\beta_s}{3}\delta_{ij}T \tag{1}$$

$$\zeta = \frac{\alpha(1-2\nu)}{2G(1+\nu)}\sigma_{kk} + \frac{\alpha^2(1-2\nu)^2(1+\nu_u)}{2G(1+\nu)(\nu_u-\nu)}p - \phi(\beta_f - \beta_s)T \tag{2}$$

ε_{ij} is change of strain of the rock, σ_{ij} is the change of stress of the rock (tension positive), p, T and ζ are the change of pore pressure, temperature and pore volume, respectively. The rock property constants are as follows: α is Biot's coefficient, ν and ν_u are the drained and undrained Poisson's ratios, G is the bulk shear modulus, B is Skempton's pore pressure coefficient, β_s and β_f are the volumetric thermal expansion coefficient of the solid and the pore fluid, respectively.

Using Eqs. (1) and (2), the boundary element solution for thermo-poroelasticity can be expressed as: (Ghassemi and Zhang, 2006):

$$\Delta p(x,y,t) = p^{dn}(x,y,t)\Delta D_n + p^{ds}(x,y,t)\Delta D_s + p^{q}(x,y,t)\Delta q_{\text{int}} + p^{T}(x,y,t)\Delta q_{h-\text{int}} \tag{3}$$

$$\Delta\sigma_{ij}(x,y,t) = \sigma_{ij}^{dn}(x,y,t)\Delta D_n + \sigma_{ij}^{ds}(x,y,t)\Delta D_s + \sigma_{ij}^{q}(x,y,t)\Delta q_{\text{int}} + \sigma_{ij}^{T}(x,y,t)\Delta q_{h-\text{int}} \tag{4}$$

The above equations consider a thin fracture segment of length $2a$ (Fig. 1) in an infinite porous matrix. Using these equations, we can find the pore pressure and stress caused by a normal and shear dislocation (ΔD_n and ΔD_s), fluid flux (Δq_{int}) and heat flow rate ($\Delta q_{h\text{-}int}$), at a point (*x*,*y*) at a time *t*. Here, Δq_{int} is the fluid leakoff rate, and $\Delta q_{h\text{-}int}$ is the heat flux rate (between fracture and matrix) per unit fracture length. The superscript "*dn*" is the normal displacement discontinuity source, "*ds*" is the shear displacement discontinuity source, "*q*" is the fluid source and "*T*" is the heat source. $p^{dn}(x,y,t)$, $p^{ds}(x,y,t)$,$p^{q}(x,y,t)$, and$p^{T}(x,y,t)$represent the pore pressure due to a unit continuous opening displacement discontinuity, shear displacement discontinuity, fluid source, and heat source, respectively. Similarly, $\sigma_{ij}{}^{dn}(x,y,t)$,$\sigma_{ij}{}^{ds}(x,y,t)$, $\sigma_{ij}{}^{q}(x,y,t)$, and $\sigma_{ij}{}^{T}(x,y,t)$are the stress components due to those sources. For the conductive case considered in this work, the equation for the temperature induced by a heat source at a point (*x*,*y*) and at time *t* is:

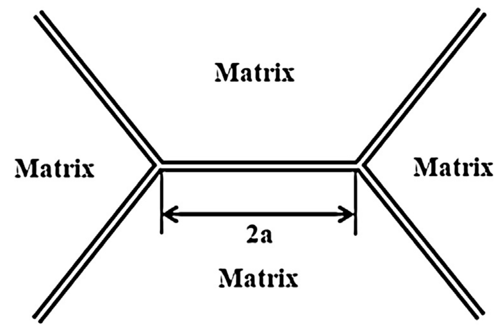

Fig. 1. Illustration of a fracture segment in a fracture-matrix system.

$$\Delta T(x,y,t) = T^{T}(x,y,t)\Delta q_{h-\text{int}} \tag{5}$$

where $T^{T}(x,y,t)$ is the temperature due to a unit continuous heat source. This and other fundamental solutions can be found in Ghassemi and Zhang (2006). For a multi-fracture system, there are interactions among fracture segments. The induced temperature, pore pressure, normal and shear stress on the i^{th} fracture segment by all fracture segments can be obtained by using the spatial and temporal superposition of the fundamental solutions (Eqs. (6–9)): (for more details see Tao and Ghassemi, 2010; Ghassemi and Zhang, 2006; Curran and Carvalho, 1987):

$$\Delta \overset{i}{T}(t) = \sum_{j=1}^{m} \overset{ij}{T}{}^{T}(t)\Delta \overset{j}{q}_{h-\text{int}} \tag{6}$$

$$\Delta \overset{i}{p}(t) = \sum_{j=1}^{m} \overset{ij}{p}{}^{dn}(t)\Delta \overset{j}{D}_n + \sum_{j=1}^{m} \overset{ij}{p}{}^{ds}(t)\Delta \overset{j}{D}_s + \sum_{j=1}^{m} \overset{ij}{p}{}^{q}(t)\Delta \overset{j}{q}_{\text{int}} + \sum_{j=1}^{m} \overset{ij}{p}{}^{T}(t)\Delta \overset{j}{q}_{h-\text{int}} \tag{7}$$

$$\Delta \overset{i}{\sigma}_n(t) = \sum_{j=1}^{m} \overset{ij}{\sigma}{}_n^{dn}(t)\Delta \overset{j}{D}_n + \sum_{j=1}^{m} \overset{ij}{\sigma}{}_n^{ds}(t)\Delta \overset{j}{D}_s + \sum_{j=1}^{m} \overset{ij}{\sigma}{}_n^{q}(t)\Delta \overset{j}{q}_{\text{int}} + \sum_{j=1}^{m} \overset{ij}{\sigma}{}_n^{T}(t)\Delta \overset{j}{q}_{h-\text{int}} \tag{8}$$

$$\Delta \overset{i}{\sigma}_s(t) = \sum_{j=1}^{m} \overset{ij}{\sigma}{}_s^{dn}(t)\Delta \overset{j}{D}_n + \sum_{j=1}^{m} \overset{ij}{\sigma}{}_s^{ds}(t)\Delta \overset{j}{D}_s + \sum_{j=1}^{m} \overset{ij}{\sigma}{}_s^{q}(t)\Delta \overset{j}{q}_{\text{int}} + \sum_{j=1}^{m} \overset{ij}{\sigma}{}_s^{T}(t)\Delta \overset{j}{q}_{h-\text{int}} \tag{9}$$

where *m* denotes the total number of fracture segments, the superscript *ij* denotes the influence of j^{th} fracture segment on the i^{th} fracture segment, and the subscript *j* denotes the source strength of j^{th} fracture segment.

To consider the time variation of the discontinuities strengths (ΔD_n, ΔD_s, Δq_{int} and $\Delta q_{h\text{-}int}$), we use a time marching scheme (e.g., Tao et al., 2011) whereby we discretize the source strengths